Recent Studies of PV Performance Models

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- I spent 19 years with BP Solar on measurements and modelling of crystalline and thin film PV indoors and outdoors

- Since Feb 2008 I have been an independent PV consultant

Recently, clients have been asking questions such as

"We've compared our modules with those of our competitors, both indoors and outdoors, so how come a simulation program gives very different answers for relative kWh/kWp from what we expect ?"

and

"We've designed a 5MWp plant with simulation program and guaranteed the banks the predicted kWh/kWp is exactly what it will produce"

INTRODUCTION

- Some PV manufacturers claim up to 33% higher kWh/kWp than competitors (usually c-Si) due to 'thermal, spectral, low light and angle of incidence improvements'

- Many recent <u>independent</u> tests worldwide show <±5% kWh/kWp

- kWh/kWp is <u>dominated</u> by [Pmax ACTUAL/Pmax NOMINAL] i.e. nameplate allowance vs. actual degradation and annealing

- Some PV simulation programs (PVSPs) predict >5% kWh/kWp differences (usually better for thin film)

- The assumptions made and algorithms used in five+ different PVSPs have been investigated

Recent studies have shown a **smaller** kWh/kWp variation than some earlier ones

PV modules have been <u>improving</u> efficiency by <u>lowering</u> losses

- Higher Rshunt from better processing and checking
- Better light capture – AR, texturing, windows, reflectors
- Improved material performance and uniformity
- Lower cell mismatching, rejection of underperforming strings
- Smaller I^2R loss from better tabbing and finger resistivities
- Better matching of multi junction devices
- Lower degradation and less allowance from nameplate
- More accurate calibrations at manufacture

Both c-Si and Thin Film now have a <u>more constant efficiency</u> across different weather conditions and will <u>expect less variation</u> in kWh/kWp than earlier measurements may have suggested

- **You can't calibrate your models on old modules !**
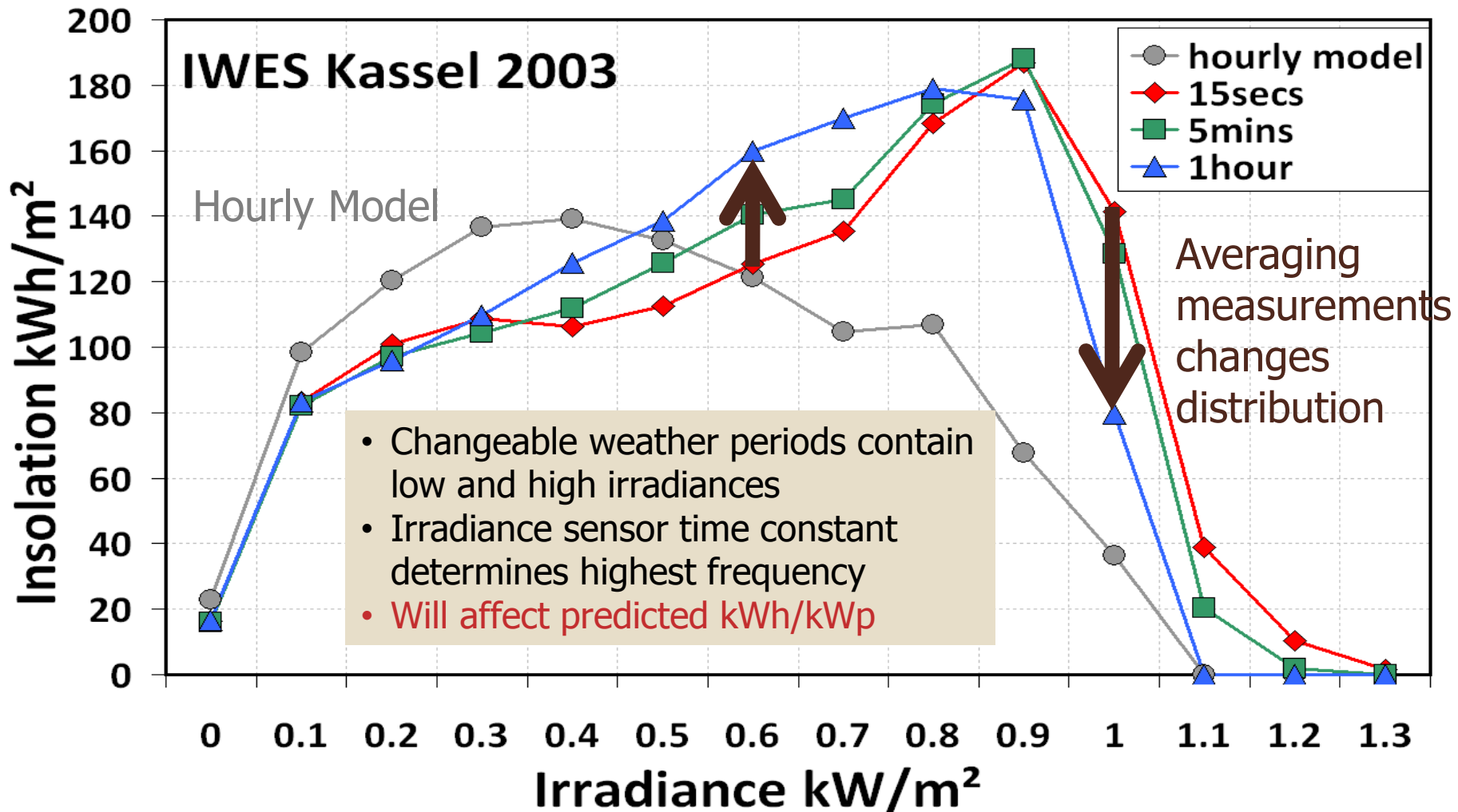
A frequent statement :
"My PVSP gives approximate values of kWh/kWp therefore it is validated"

- kWh/kWp depends on the product of >4 items

| Insolation (Gi, Tm) | ✶ | Unknowns e.g. Dirt, Pmax/Nominal | ✶ | PV Efficiency (Gi, Tm) | ✶ | Inverter Efficiency (Gi, Tm) |
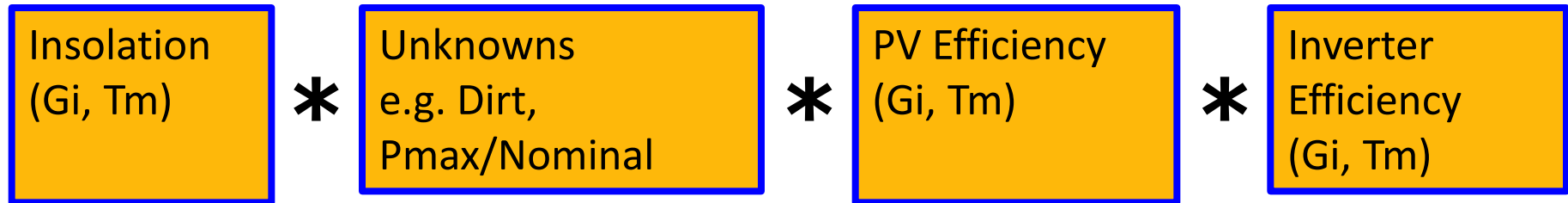
- Errors may self cancel

- Exact fits to measured kWh/kWp can be made by "adjusting" unknowns such as soiling – these are then technology or site dependent

- **Every stage must be checked to be correct to validate a simulation, not just the sum of kWh/kWp**

- **Don't just validate one module at one site !**

Averaged (hourly) <u>insolation vs. irradiance</u> <u>predicts more energy at low light</u> level than occurs

IWES Kassel 2003

Hourly Model

Legend:
- hourly model (grey circles)
- 15secs (red diamonds)
- 5mins (green squares)
- 1hour (blue triangles)

Y-axis: Insolation kWh/m²
X-axis: Irradiance kW/m²

- Changeable weather periods contain low and high irradiances
- Irradiance sensor time constant determines highest frequency
- Will affect predicted kWh/kWp

Averaging measurements changes distribution

Measured efficiency vs. irradiance
Low and High clearness conditions (IWES Kassel)

Averaged low light efficiency depends on overcast: clear ratio (site specific)

(if high horizon east/west) Hides redder light from low sun
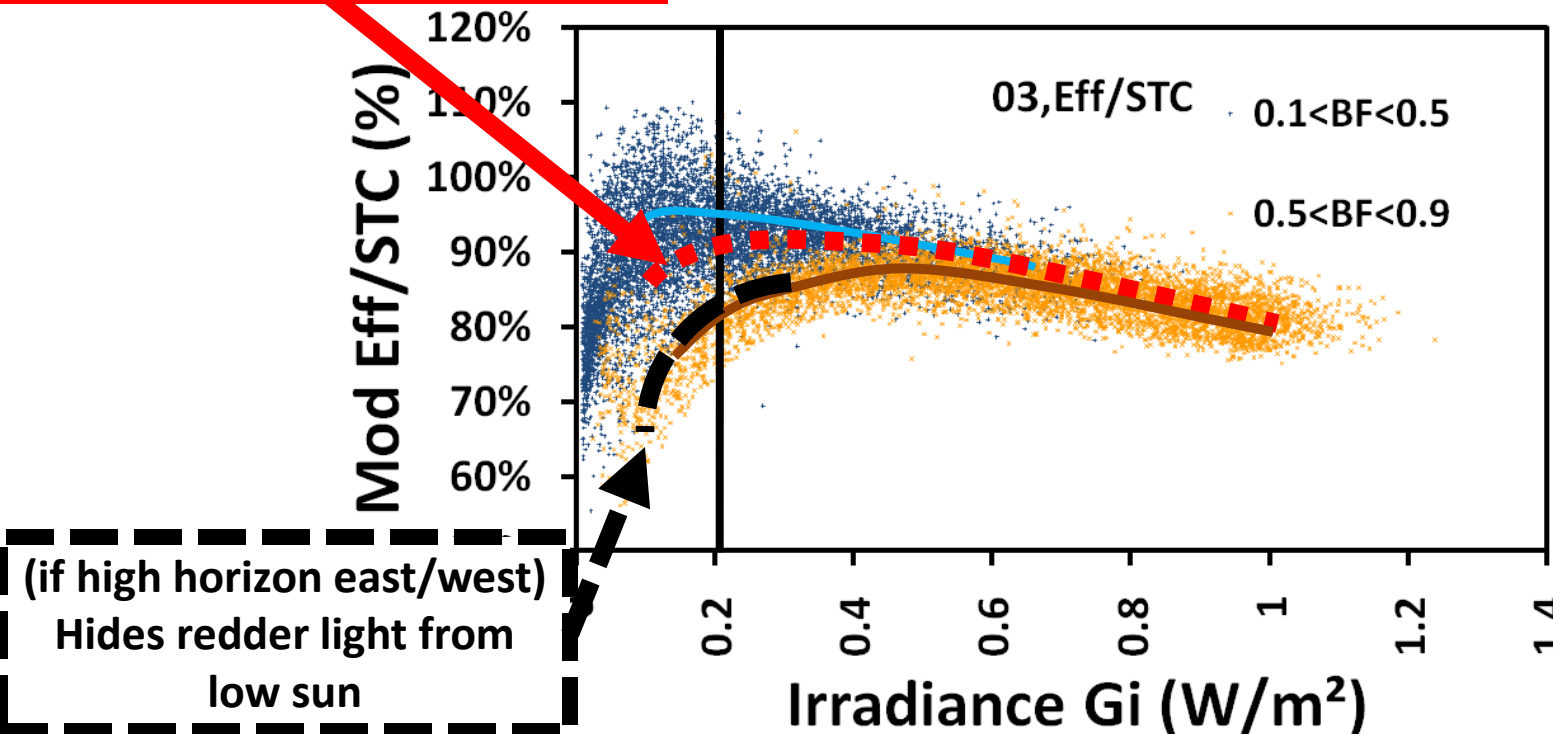
Apparent low light performance is site specific and will depend on relative sensor spectral response

kWh/kWp modelling uncertainty depends on many factors

Reference module calibration	**>±2.5%**	c-Si, less accurate for thin films (< ±10% ??)
Flash tester repeatability	**x% (1%?)**	(Not perfect AM1.5 spectrum, capacitance)
Nameplate allowance LID/degradation	**-1 to -3%** **-10 to -35%**	B doped p type c-Si, 0% for n-type ? greater for thin films
Pmax bin width W	**~±2.5%**	e.g. 200<Pmax<210W or 78<Pmax<82 W
Insolation sensor calibration	**~±2-3%** **~±1.7-7%** **???**	Pyranometer calibration, deterioration Reference cell calibration, deterioration Satellite data, Tilted plane algorithms
Yearly insolation	**~±4%/y**	Random variations, more for el Niño etc.
Dirt loss	**?**	Site dependent, falls after ~>5mm rain
KWh/kWp	$U^2 = u_1^2 + u_2^2 \ldots u_n^2$	**Total uncertainty depends on all above - lowest possible** $(2.5\%)^2+(1\%)^2+(2.5\%)^2+(2\%)^2 \rightarrow$ **4.2%**

Minimum variability of PV parameters per Power bin –
example Thin Film from manufacturers' datasheet

$$\Delta \mathbf{Pmax} = \Delta \mathbf{Vmpp} + \Delta \mathbf{Impp}$$
$$= \Delta \mathbf{Voc} + \Delta \mathbf{FF} + \Delta \mathbf{Isc}$$
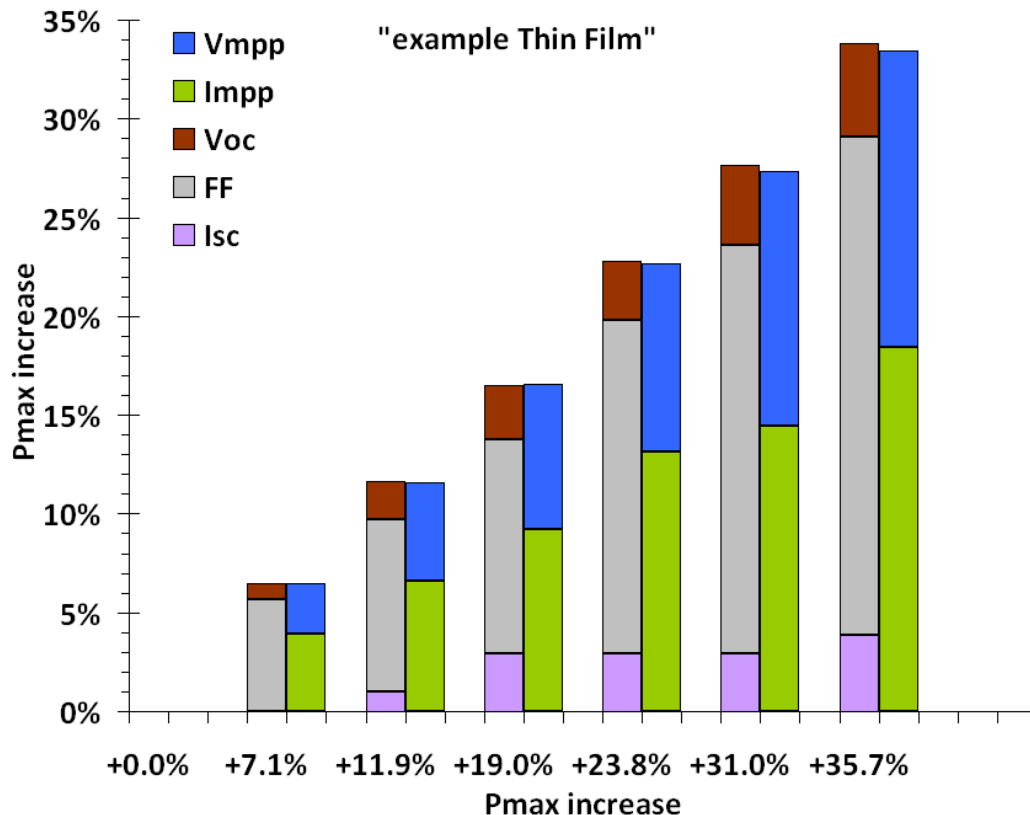
- Shows minimum parameter variation within a range of modules, reality will be higher

- e.g. TF has 6% Pmax bins so will be >3% Imp and >3% Vmp variation each Pmax bin

- c-Si : Power tends to follow Isc more than Voc or FF

- Models must account for variability

How simulation programs usually calculate kWh/kWp (Matrix method)

$$kWh/kWp \; \alpha \; \sum Insolation_{(Tmod, Irradiance.)} * Efficiency_{(Tmod, Irradiance)}$$

Insolation kWh/m²

Efficiency /STC
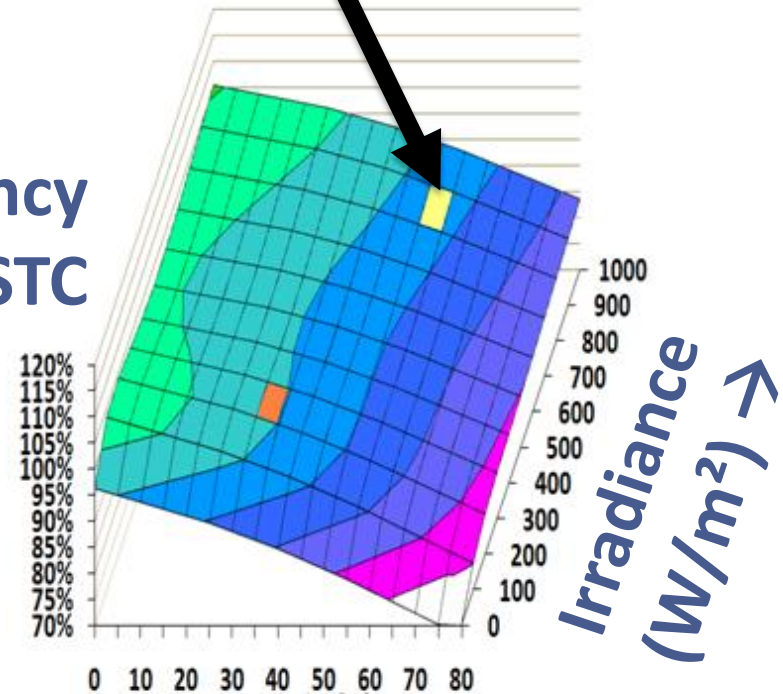
Irradiance (W/m²) →

Module Temperature →

Averaging weather data to hourly values distorts the distribution towards lower irradiances

How simulation programs usually calculate efficiency (Matrix method)

Low Light efficiency change Eff@200/Eff@1000 - 1

Pmax rate of fall =1/Pmax*dP/dT

Efficiency /STC

Modelled Efficiency(G,T) depends on assumed

- Low light efficiency change

- Pmax drop with temperature gamma

Irradiance (W/m²) →
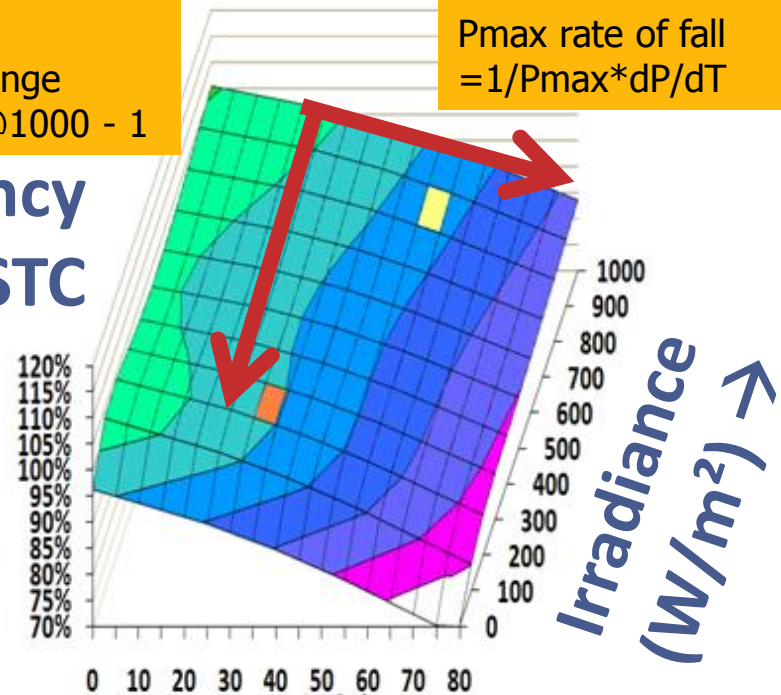
Module Temperature →

PVSPs usually use a 1 diode model fitted to an IV curve
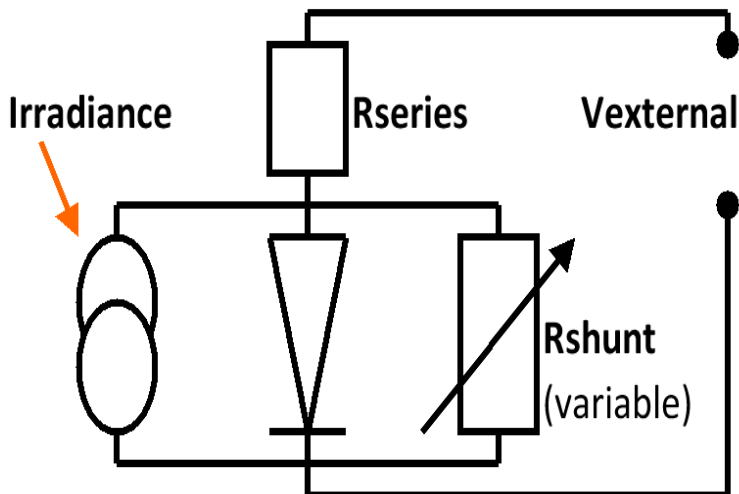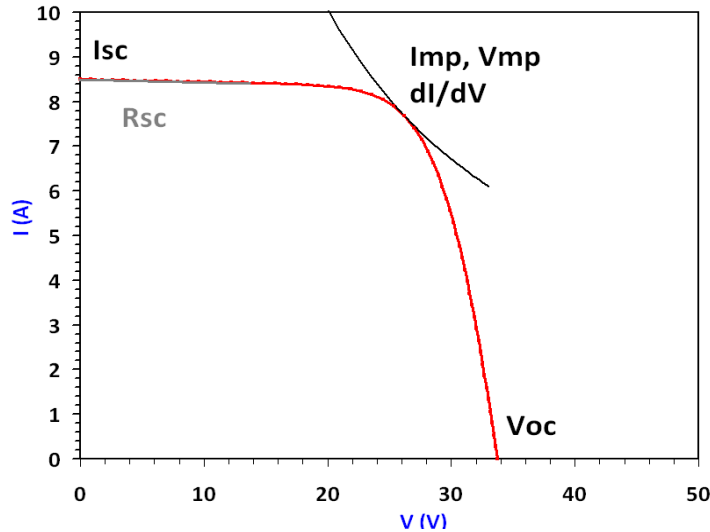
- Fitted to data sheets or a tested module
- What will variability be module to module ?
- Published model also predicts
  - Pmax temperature dependence
    - not IEC 61215/61646
  - LLEC "low light efficiency change"
    - not EN 50380
- Rsc (Resistance at Isc)
  - estimated as not on datasheet
  - will vary for each module
  - may depend on bias dependent collection and cell mismatch
  - known to rise as irradiance falls – but how best to model this ?

PV efficiency/nominal vs. irradiance and module temperature :

- PVSPs contain databases of physical, thermal and electrical parameters

- They can create graphs and export their values as tables to be further analysed

- Graph shows <u>how to check</u> Gamma (1/P*dP/dT) and LLEC (low light efficiency change Eff@200/Eff@1000 - 1) from datasheets with simulation programs
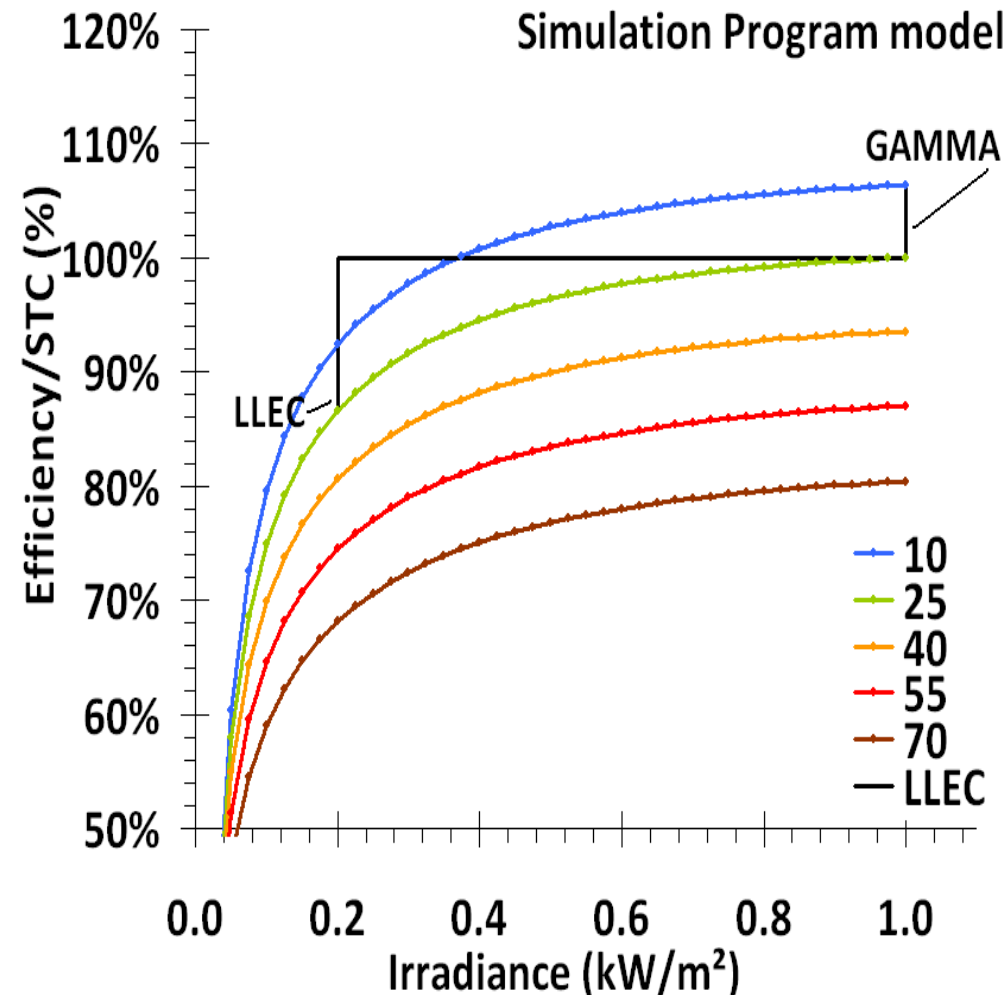
Checking gamma = 1/P*dP/dT
5 PVSPs vs. Manufacturer datasheet

Checking Low Light efficiency changes
5 PVSPs vs. Manufacturer datasheet

c-Si S5 modelled
+0% vs. -31%

Efficiency /STC
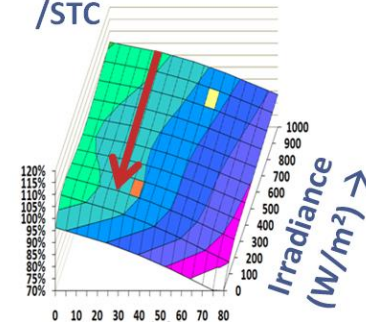
Module Temperature →
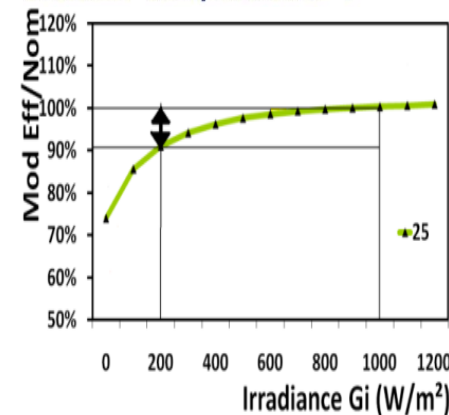
Manufacturer

■ Program V1
▲ Program W1
■ Program X2
◆ Program Y2
● Program Z1
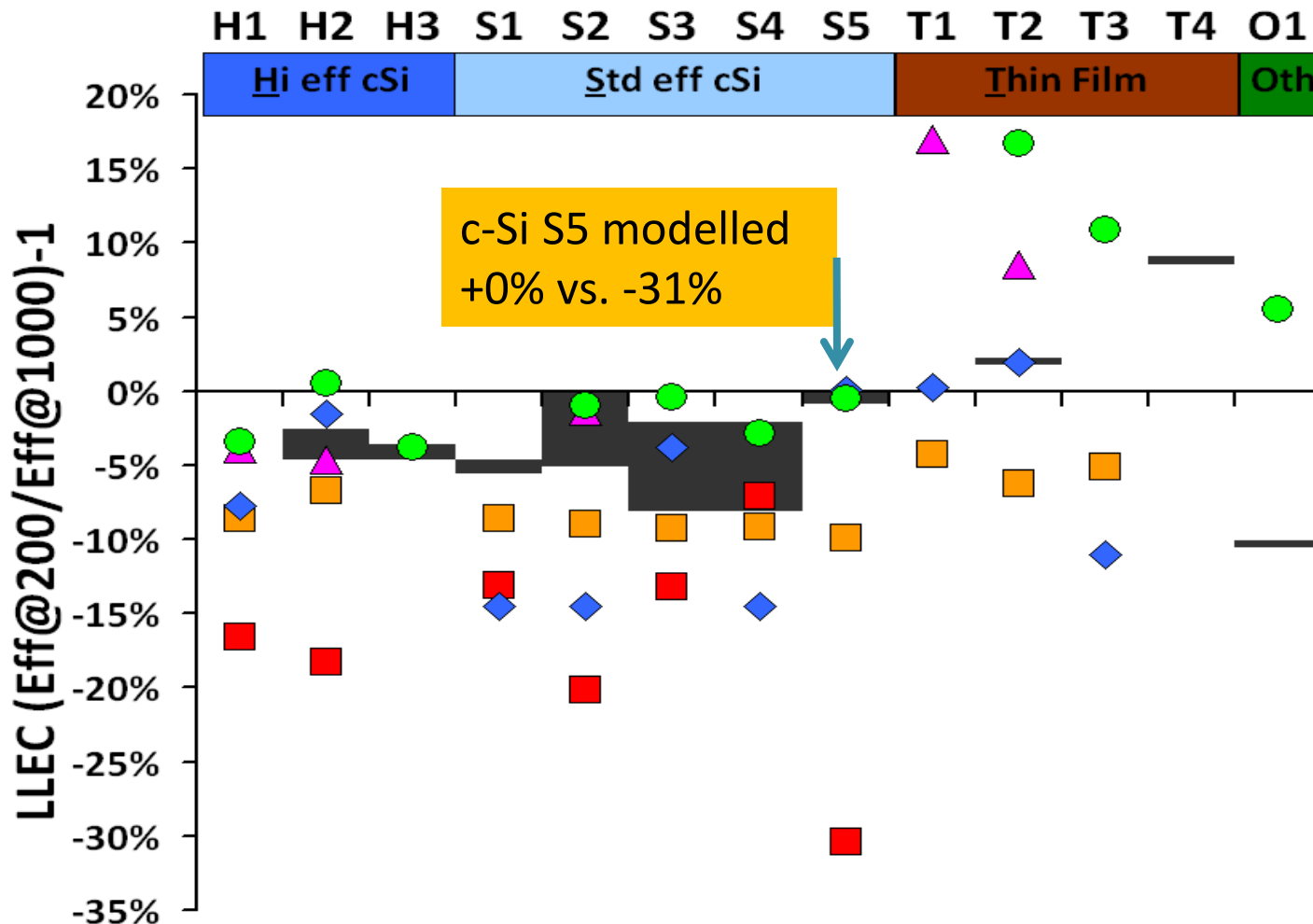
PVSP : <u>predicted</u> kWh/kWp vs. Gamma and LLEC in databases (not manufacturer data) for 11 PV module types
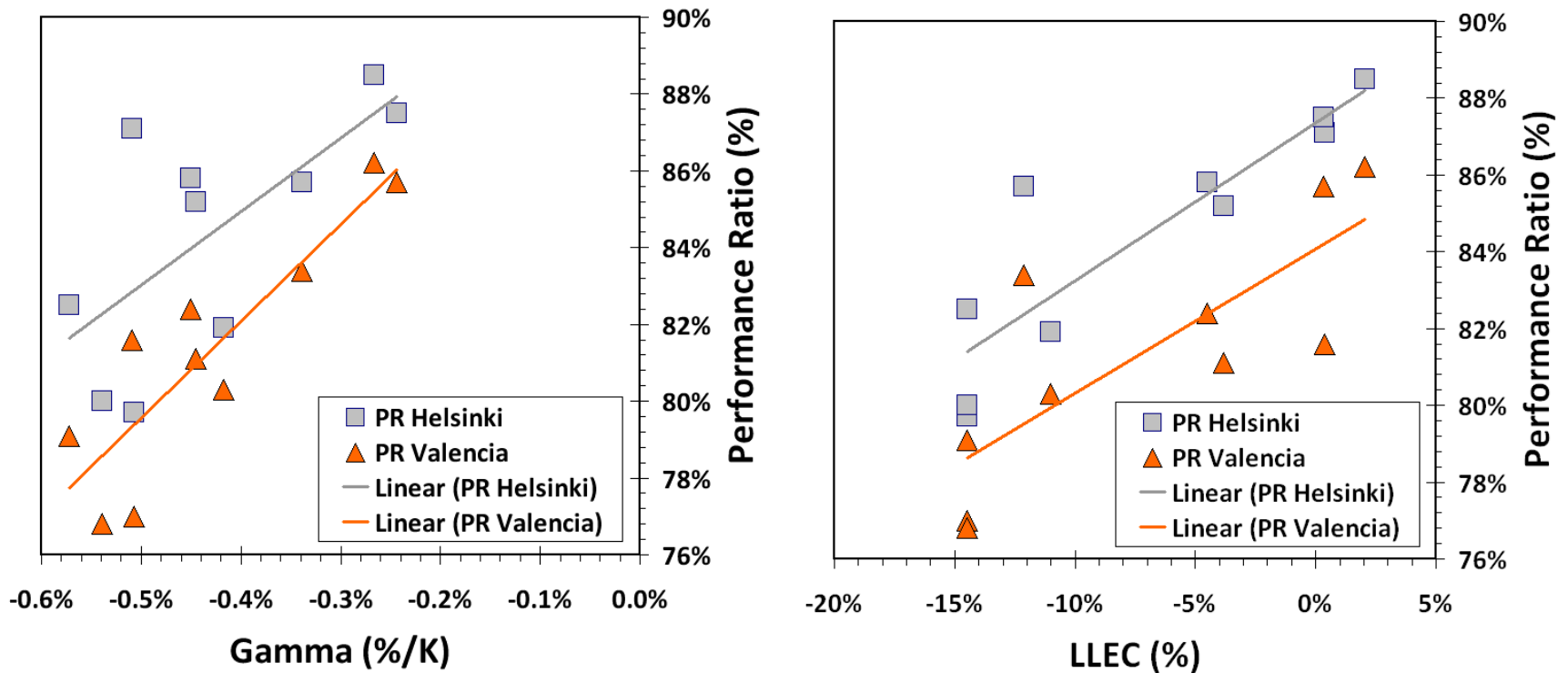
- **Strong correlation of Performance Ratio with both Gamma and LLEC**

- **Any discrepancies in data will give large errors in predicted PR**

Checking kWh/kWp sensitivities to errors at 4 sites

Climate summary

	Site name, Country	Latitude °	Tilted Insolation 30°S kWh/m²	Weighted Tmodule °C $\Sigma(Tm*G)/\Sigma(G)$
	Helsinki, FI	60°N	1150 *	29 *
	Munich, DE	48°N	1350 **	33 **
	Valencia, ES	39°N	1850 ***	42 ****
	Albuquerque NM,USA	35°N	2300 ****	44 ****

## Hourly Tilted Insolation vs. Module Temperature
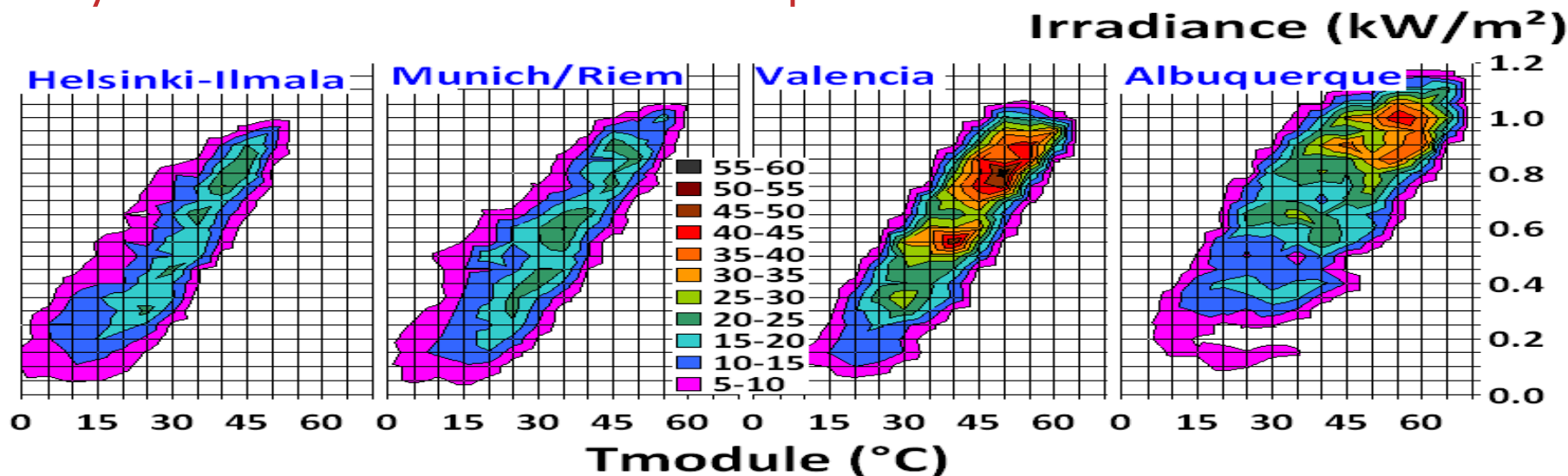
Change in predicted kWh/kWp vs. PVSP gamma error
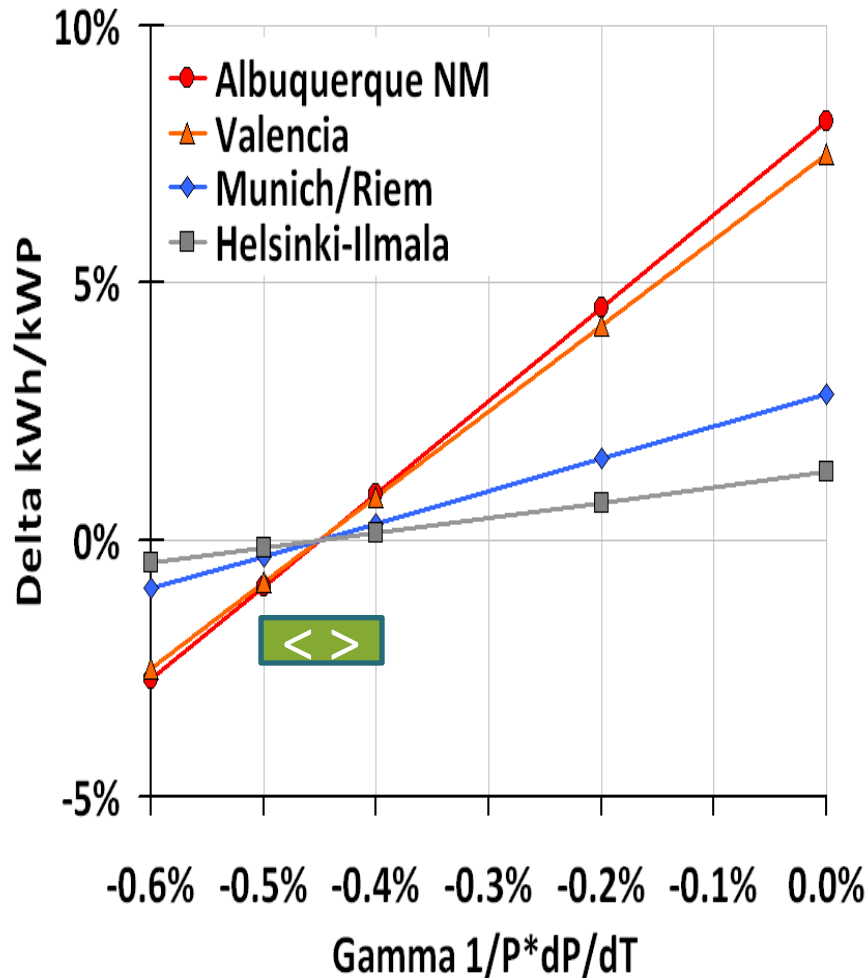

- Discrepancies in the gamma factor Pmax temperature coefficient cause the largest errors in calculated kWh/kWp for the hottest sites (as expected)

- A gamma error (as seen in simulation programs) of **±0.05%/K** causes a predicted kWh/kWp change of ±0.5% (Helsinki) to ±1% (Albuquerque)

# Change in predicted kWh/kWp vs. PVSP low light efficiency change error
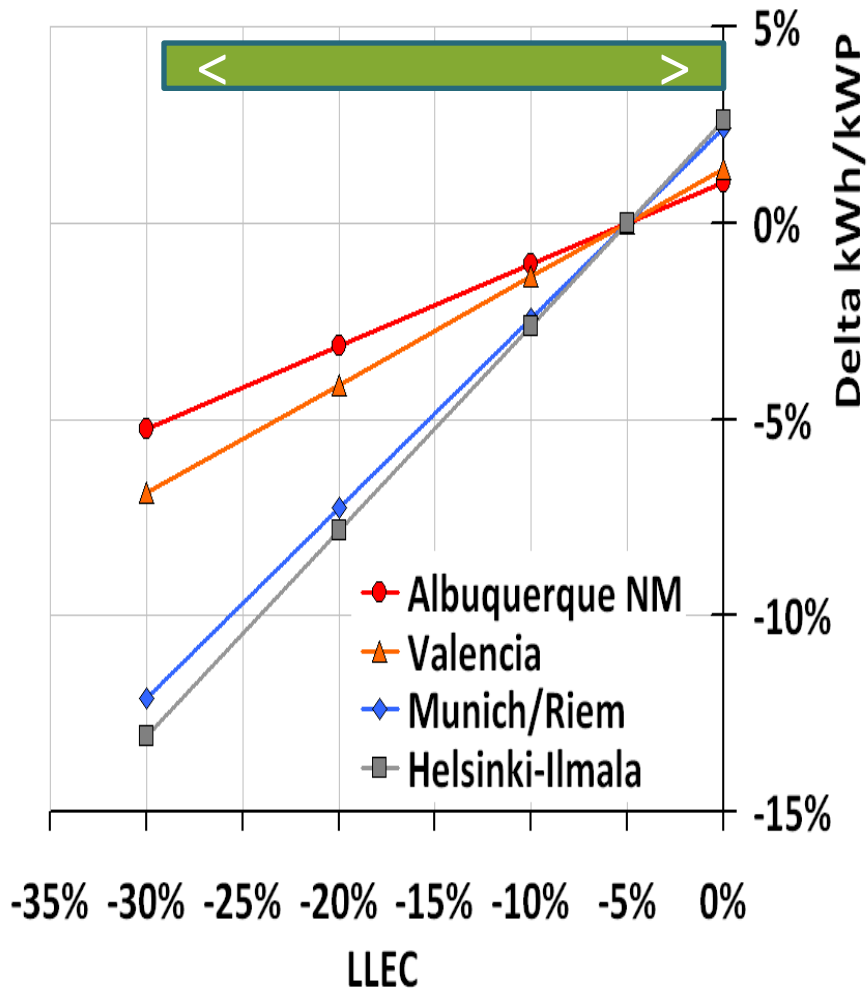
- Discrepancies in the low light efficiency change cause the biggest errors in calculated kWh/kWp for the dullest sites (as expected)

- A low light efficiency change error of **30%** (as seen in PVSPs) causes a predicted kWh/kWp change of 6% (Albuquerque) to 15% (Helsinki)

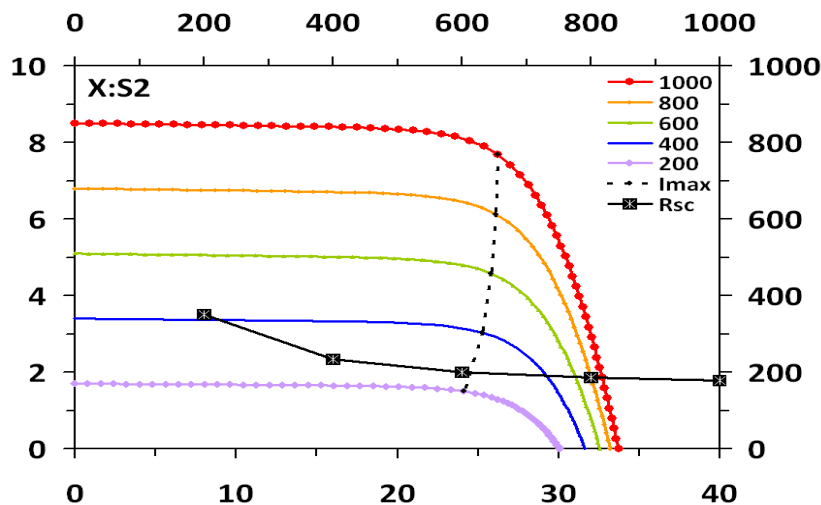# PVSP predicted IV vs. Tmodule (70C to 10C) Module S2

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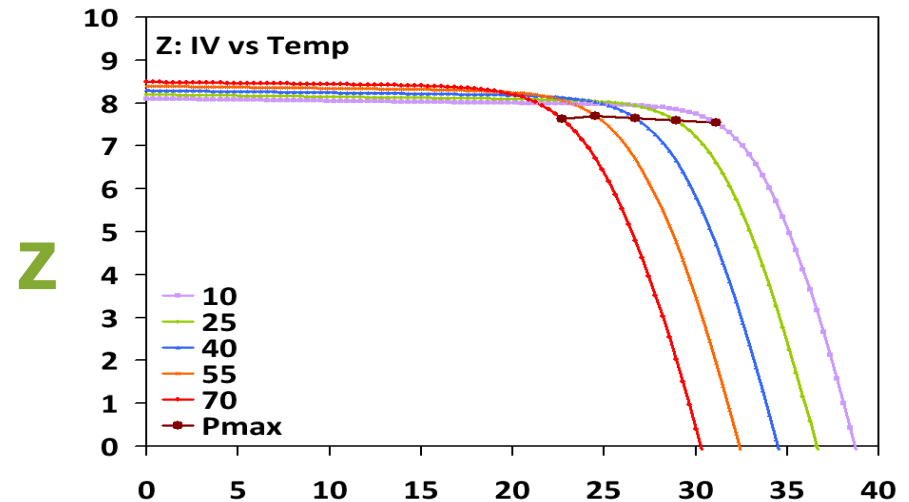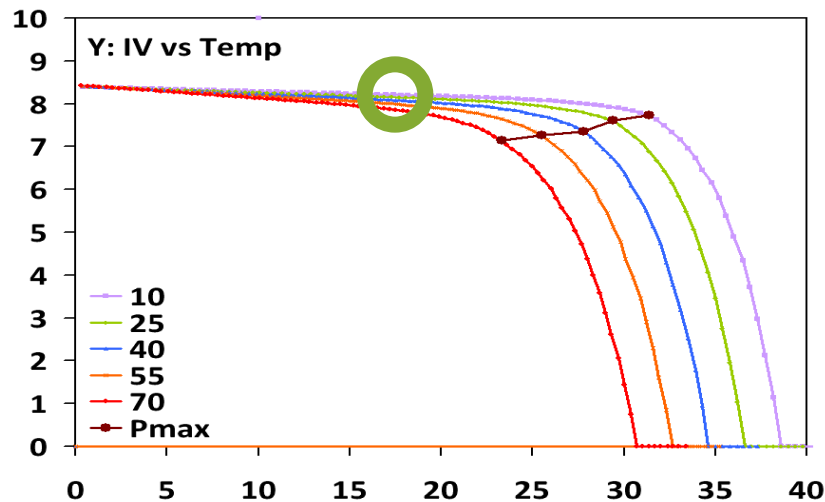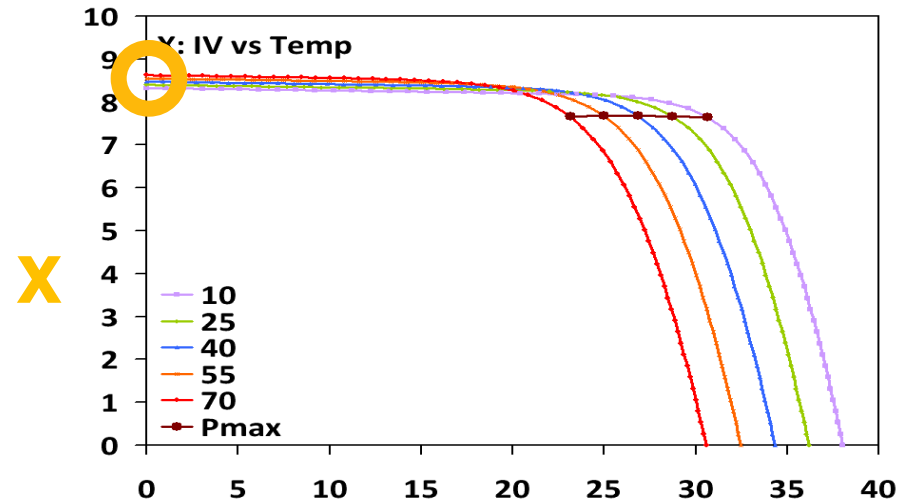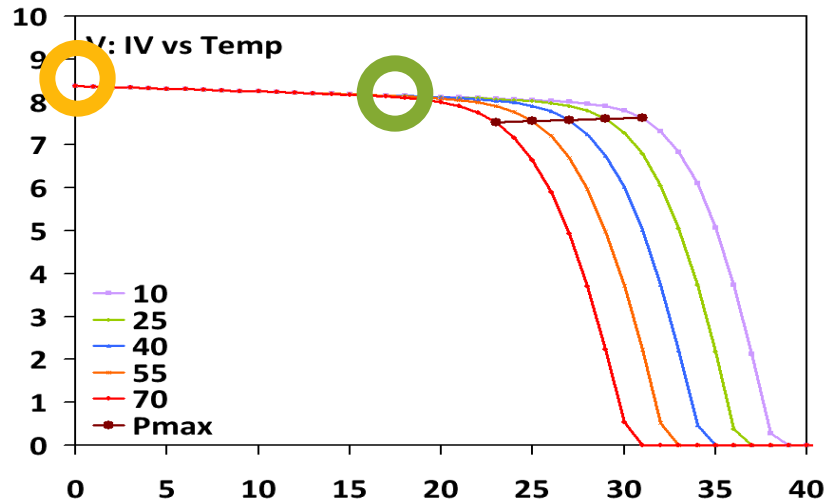
Discrepancies of 1/Isc*dIsc/dT (alpha) and Rshunt with temperature cause power temperature coefficient error
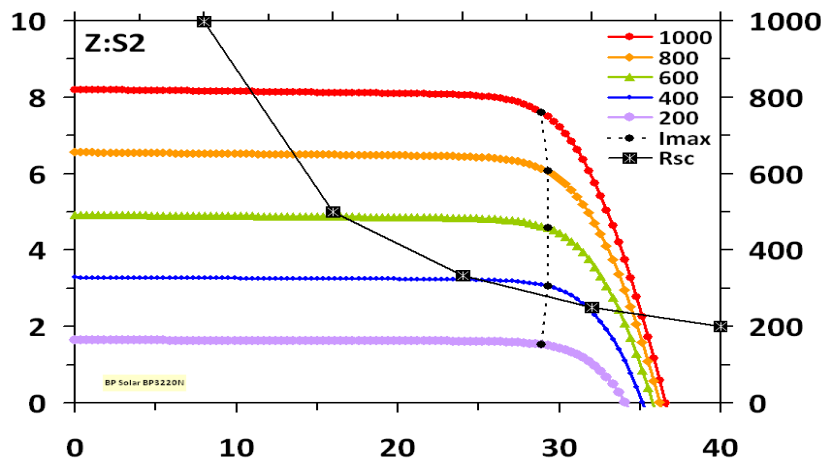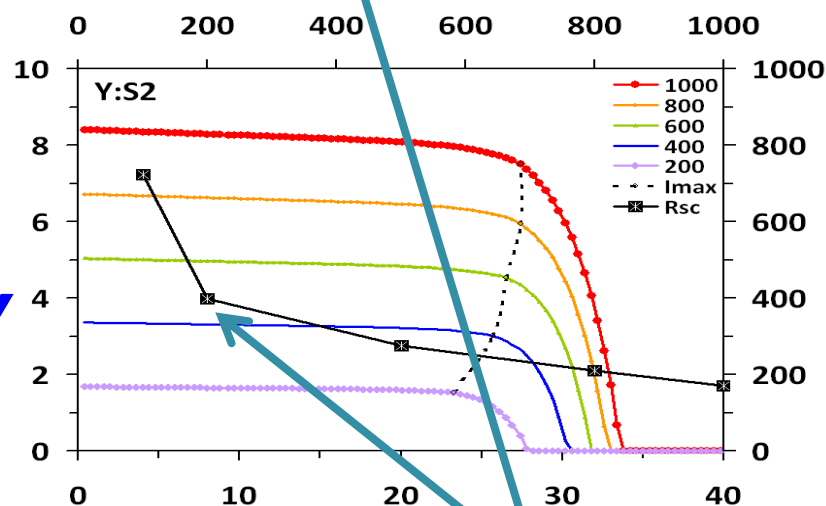
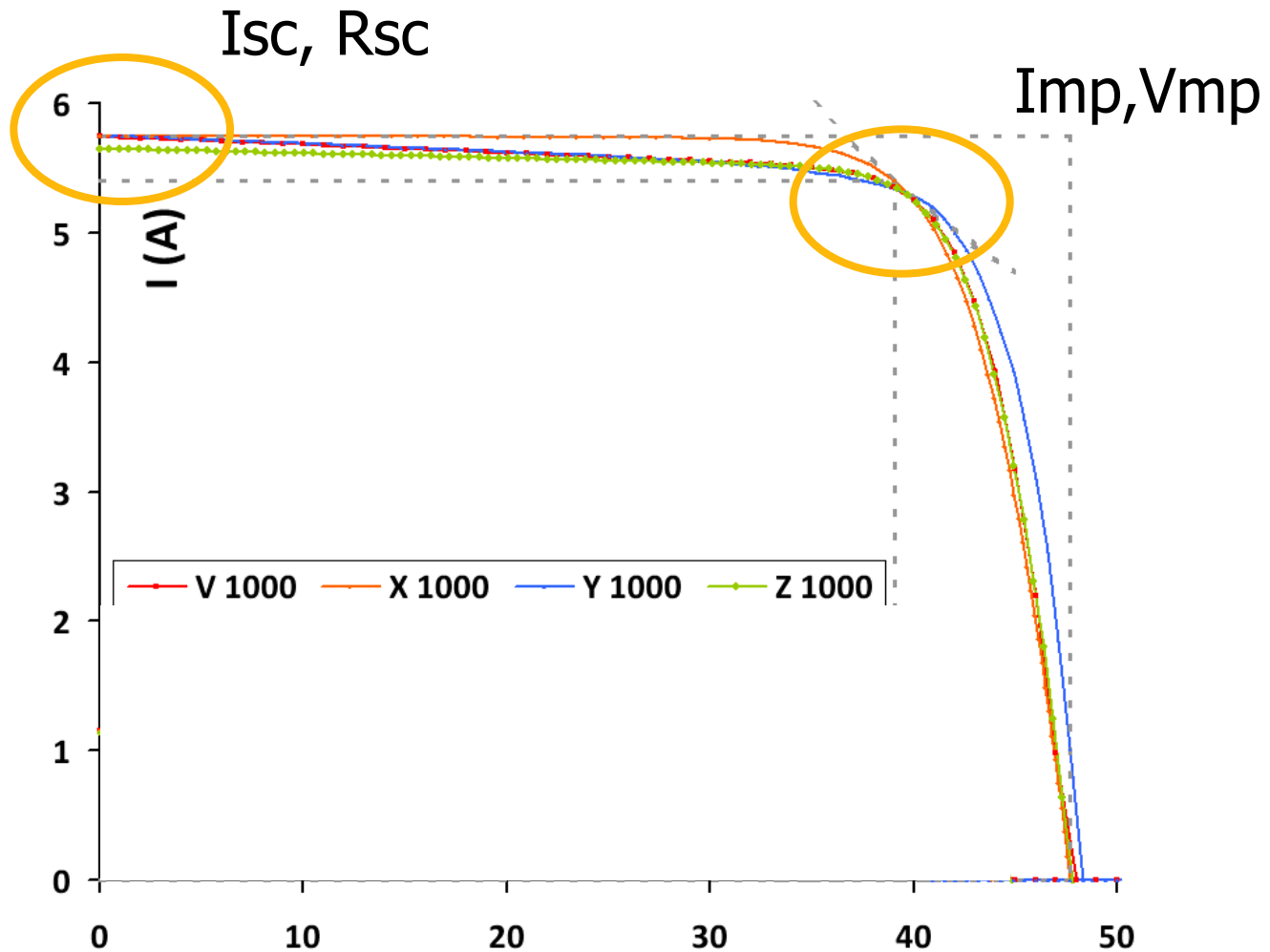# PVSP predicted IV vs. Irradiance (200-1000W/m²) Module S2

SRCL
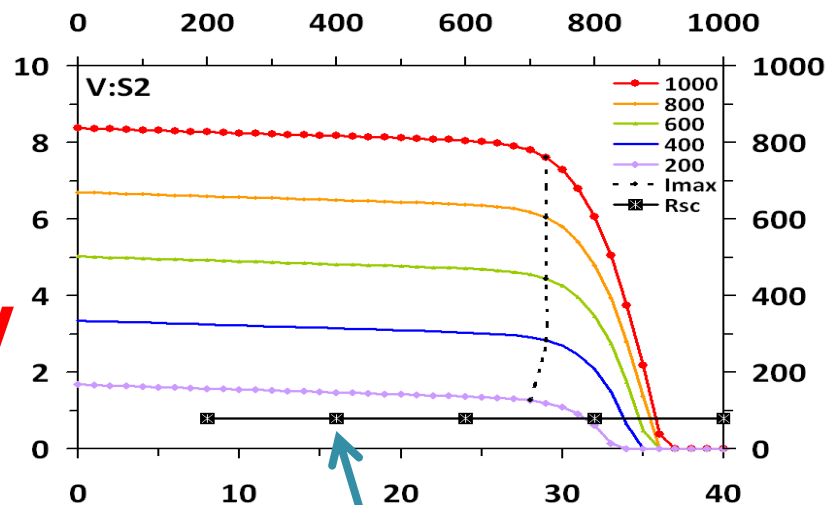
Discrepancies of Rsc(irradiance) causes LLEC difference

Isc, Rsc

Imp,Vmp

I (A)

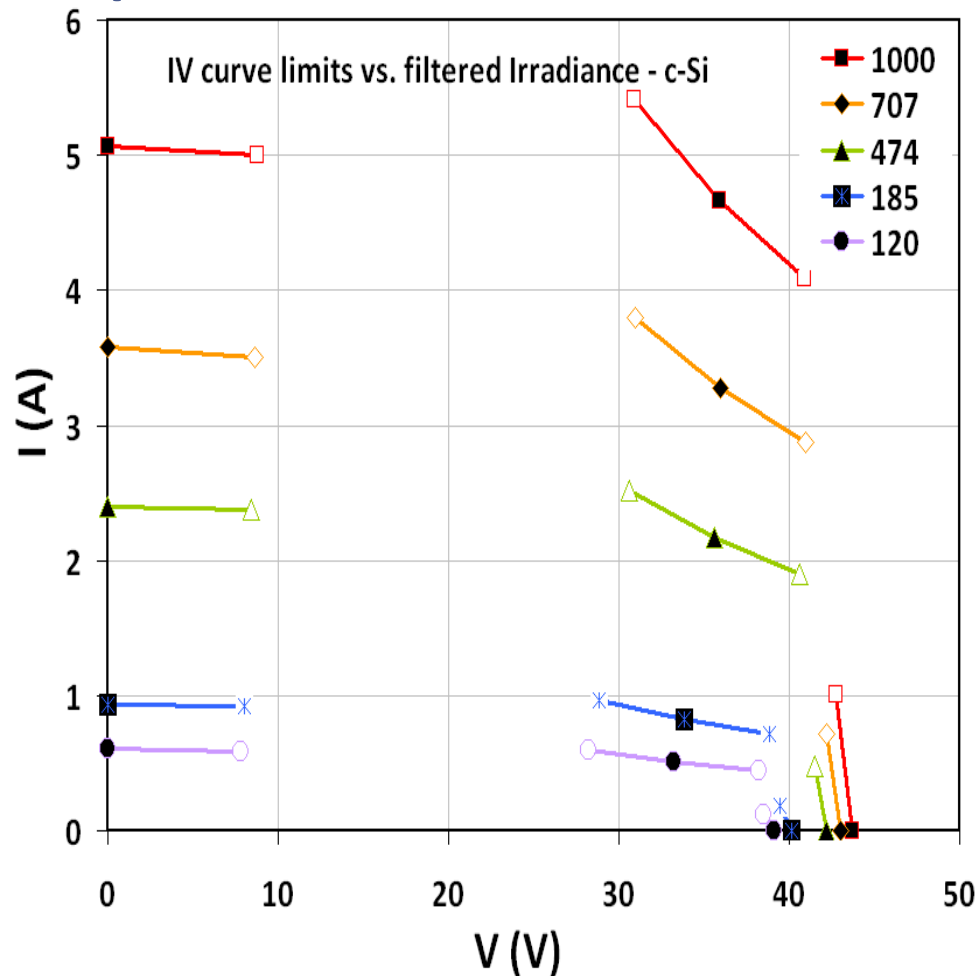V 1000   X 1000   Y 1000   Z 1000

SRCL
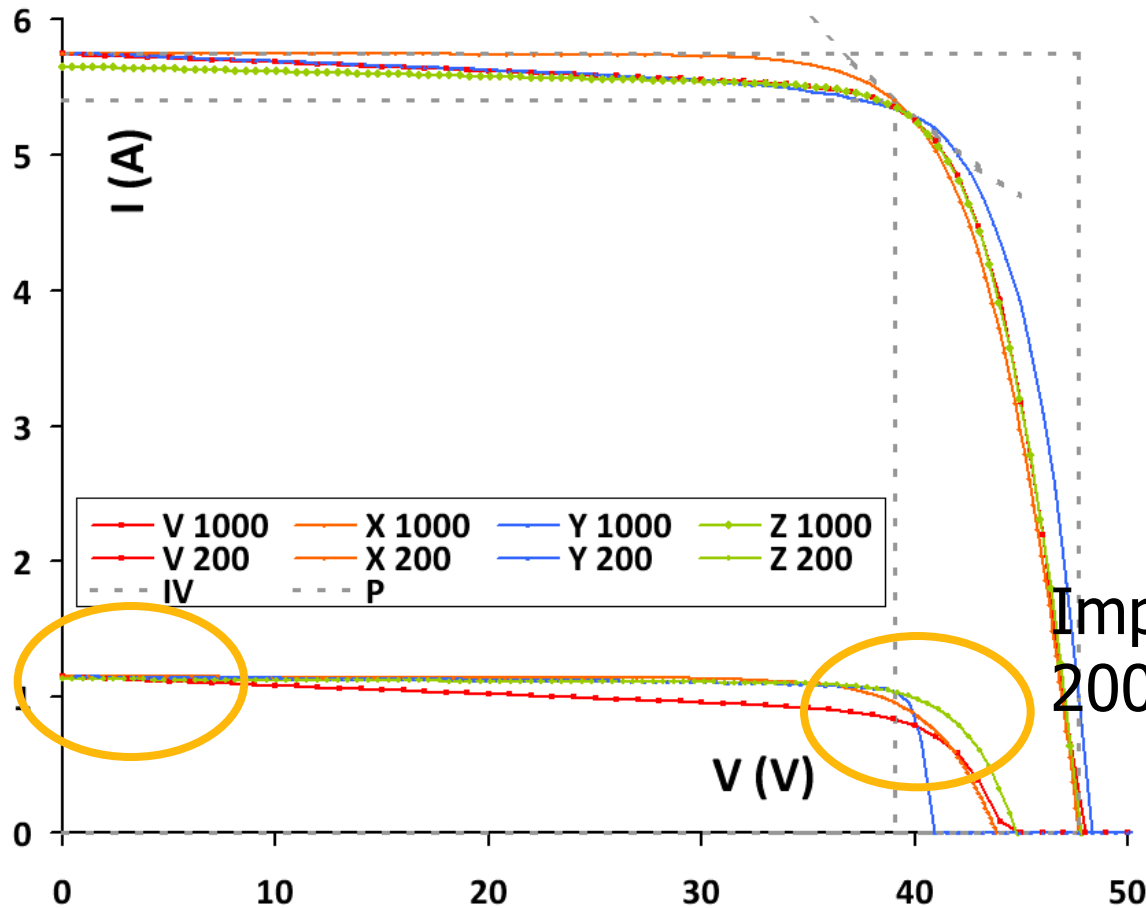
Rsc@200

Imp,Vmp@ 200

Voc@200

+

Measuring shunt Rsc vs Irradiance Indoor to EN50380
(Indoor flash + mesh, ND filters - BP Solar c-Si)
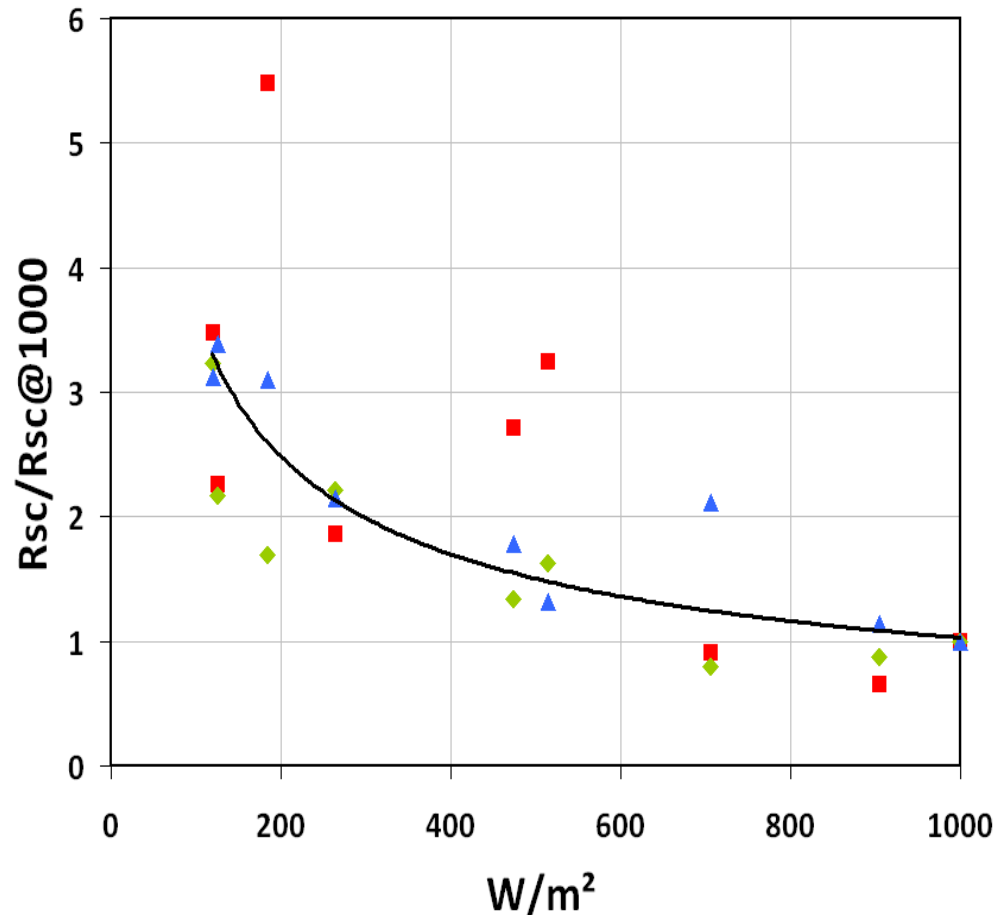

- BP Solar c-Si module measured at different irradiances using meshes and/or neutral density filters

- Black points measured

- White points tangents

- I don't have all IV data
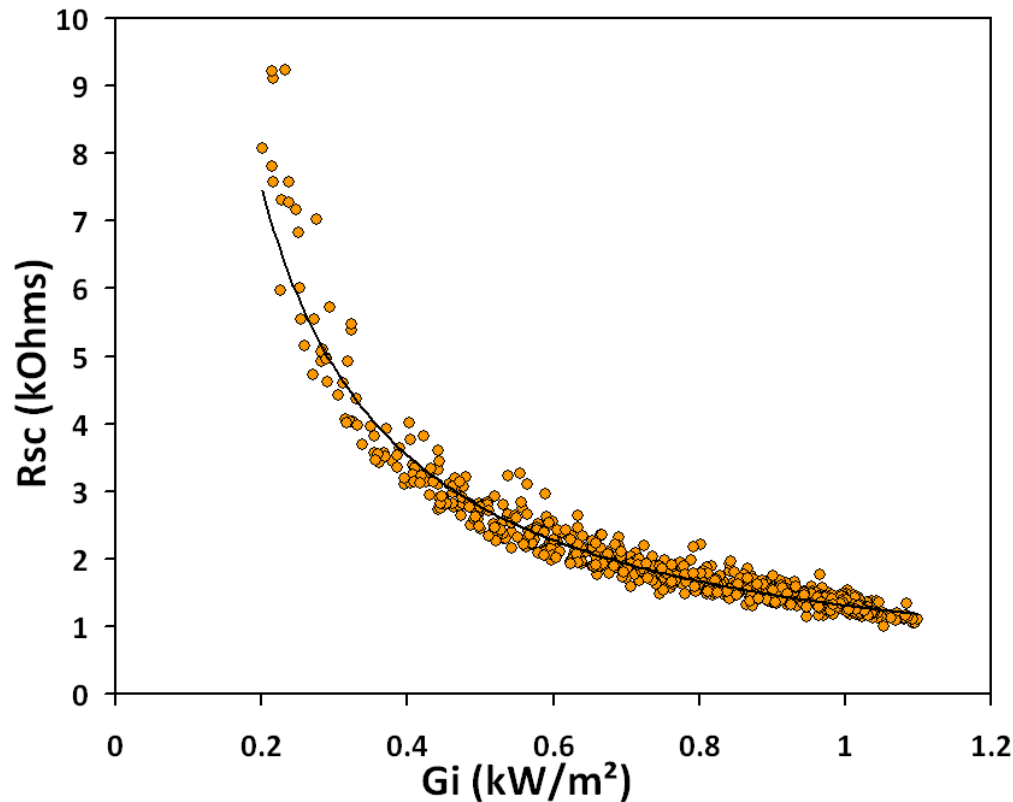
Shunt Rsc vs. irradiance
[Rsc@?W/m²]/[Rsc@1000W/m²]
Indoor flash + mesh, ND filters (BP Solar c-Si)

- Difficult to measure as Rsc is high, meshes may be non uniform, filters may not be neutral density.

- Power series fit

- 3 module types look similar

- [Rsc@200]/[Rsc@1000] may be 2.5 to 3x

Measuring shunt Rsc vs Irradiance Outdoors (Oerlikon Solar Micromorph)

- Oerlikon Solar thin film module measured outdoors in Switzerland using IV sweep data

- Rsc (kOhm)

- [Rsc@200]/[Rsc@1000] may be 4 to 5x

- But thin film starts from a lower relative value
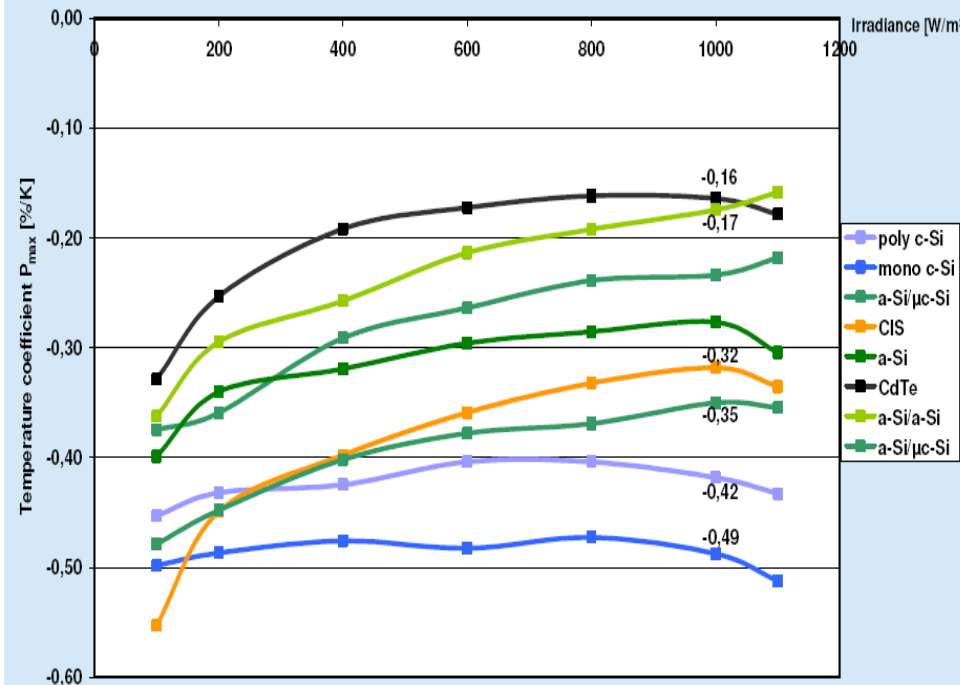
TUV indoor matrix measurements
Ulrike Jahn – Valencia world conference 2010

Gamma – vary with irradiance
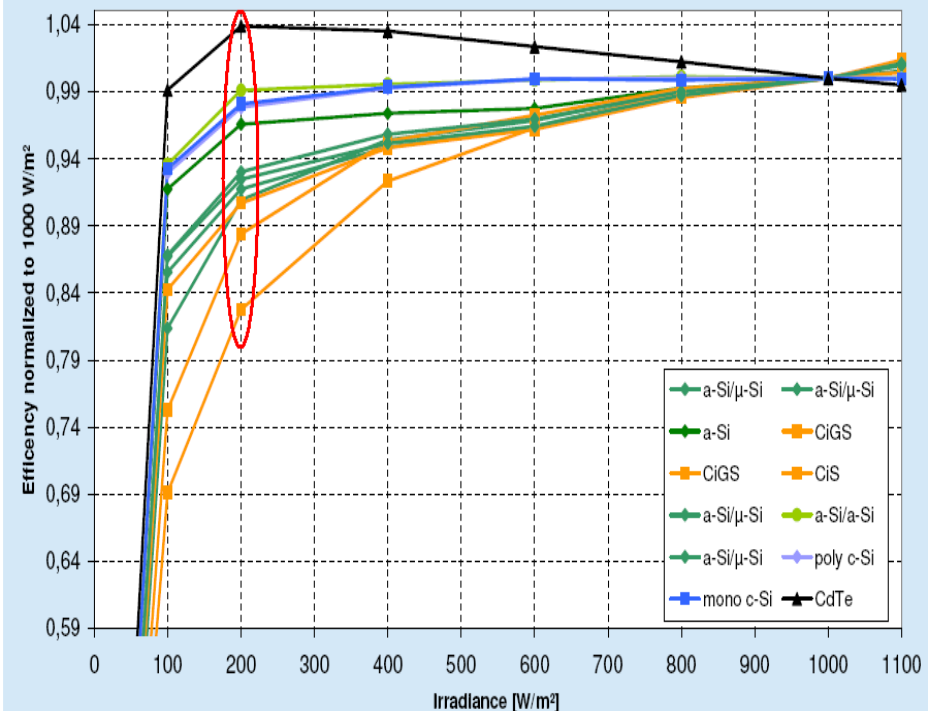
LLEC – mostly better than -8%

Temperature Coefficient P_{max}
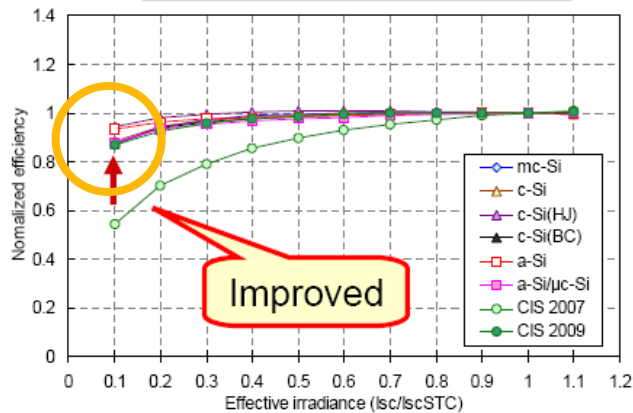Indoor Measurements for Different G_i (IEC 61853)

Module Efficiency Normalized to STC
Indoor Measurements at 25°C

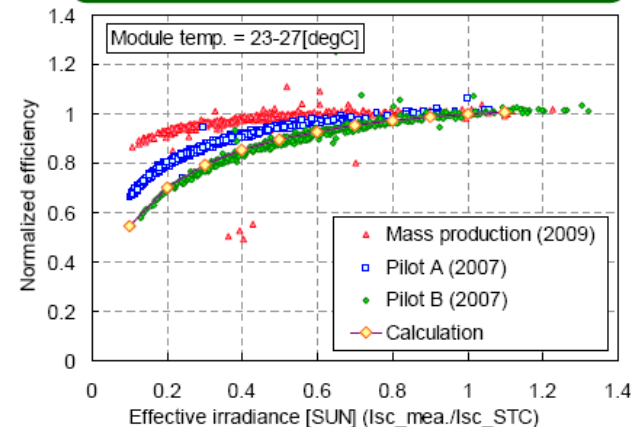7 | 25th European PV Solar Energy Conference, Valencia, Spain, 6-10 September 2010   9 | 25th European PV Solar Energy Conference, Valencia, Spain, 6-10 September 2010

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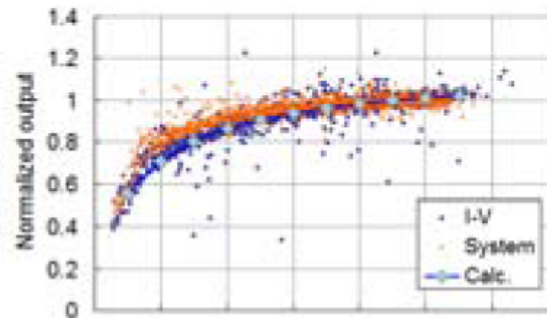
Low-light performance

What else differentiates PV technologies and by how much ?

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Independent tests of kWh/kWp < ±5%

Efficiency (5-20%) ~ 4:1	Power rating tolerance +3/-0% to +0/-10%	Max. module size m² >2:1
Wp/kg (4-22) ~ 6:1	Lifetime @ 80% Pmax **5 10 20 25 30 40+ y**	Certification CE/IEC/TUV/UL **Y/N**?
m²/1000kg (60-250) ~ 4:1	Initial degradation (~2% vs. up to 30%)	Max System Voltage ~ 500-1000 V
Cost $/Wp ~ 1.5:1 variable	Steady degradation (~-0.5 to -1%/y ?)	Aesthetics (subjective) blue □ brown |||
Wp, Imax or Vmax/mod >> 5%	Pmax T coefficient %/K ~ 2:1	Tracker (higher eff.)? Y/N

€/kWh site dependent ±???

Conclusions

- Simulation programs still use <u>different values</u> for LLEC and gamma than from manufacturers' data sheets
(measured to IEC 61215/61646 and EN 50380).

- These anomalies cause up to <u>15% error in predicted kWh/kWp</u>

- kWh/kWp does <u>not</u> differentiate the technologies well

- Rsc(Irradiance) seems very important in determining the LLEC behaviour of the PV – it's not on the specsheets

- Models need to check every stage, not just kWh/kWp/year

- Modelling one module at a site might not be able to be generalised to other modules at different locations

Thank you for your attention !

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Spare slides